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UNITED STATES
DEPARTMENT OF THE INTERIOR
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PROGRESS REPORT I

FRICTION FACTORS FOR LARGE CONDUITS FLOWING FULL

EKLUTNA, NEVERSINK AND EAST DELAWARE TUNNELS, WEBER COULEE SIPHON, SAN DIEGO AQUEDUCT

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DIVISION OF ENGINEERING LABORATORIES

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PROGRESS REPORT I
FRICTION FACTORS FOR LARGE CONDUITS FLOWING FULL-EKLUTNA, NEVERSINK AND EAST DELAWARE TUNNELS, WEBER COULEE SIPHON AND SAN DIEGO AQUEDUCT

INTRODUCTION

Engineering Monograph No. 7, "Friction Factors for Large Conduits Flowing Full", by J. N. Bradley and L. R. Thompson, was published by the Bureau of Reclamation in March 1951. Intent of the monograph is to furnish engineers up to date, practical information for accurately estimating the friction losses in pressure pipes. Information presented in the monograph introduces, for practical design use, the concept of relative roughness to enable a close evaluation of the coefficient of friction.

Friction factor information for three tunnels, one inverted siphon and sections of an aqueduct has been obtained since the monograph was published. In an effort to supplement and keep current the information in Monograph No. 7, this report publishes the friction factors from tests on these conduits.

TUNNELS

Eklutna Tunnel

Eklutna tunnel conveys water from Eklutna Lake to steel penstocks leading to a powerplant. The tunnel is 9-feet inside diameter, concrete lined, 23,550 feet long and operates under pressure. The capacity of the tunnel is 640 second-feet at a velocity of 10 feet per second, the slope of the invert being 0.0034.

The tunnel terminates at a surge tank, installed directly over the tunnel, 22,805 feet downstream of the gate shaft. This surge tank, with a restricting orifice 49-inches in diameter, has an inside diameter of 30 feet and extends 176 feet above the tunnel. Beneath the surge tank the tunnel section contains a 9 foot long, round to square transition; a square section 4 feet 6 inches long and a 9 foot long square to round transition. The surge tank orifice is located in the 9-foot-diameter section upstream of the tunnel transition.

The bulkhead gate shaft near the upstream end of the tunnel contains a transition section of the same general shape as that of the surge tank, but with a 9-foot-rectangular separation between the transitions. Approximately 950 feet of 9-foot-diameter tunnel was constructed upstream of the gate shaft.

Head loss measuring stations, providing a test reach of 22,805 feet, were located in the gate shaft and surge tank which were assumed to be large manometers connected to the tunnel. The head loss was obtained from water surface levels measured and recorded directly on water stage recorders mounted in the shaft and surge tank. Levels were transferred to the recorder by a float at the water surface. A 1-inch deflection of the recorder pen represented 1 foot of water level change in the gate shaft and 5 feet of change in the surge tank.

Discharges necessary to compute the average velocities in the tunnel were obtained from flow meter taps in the turbine spiral case. Calibration of these taps was performed during acceptance tests. Discharges for the tests were measured by the Gibson Method.

Resistance coefficients "f" computed from the equation $h_f = \frac{fl}{D}\frac{V^2}{2g}$ ranged from 0.017 to 0.014. The Reynold's Number ranged from 709,000 to 4,640,000 respectively. These results are contained in Table 1 and have been plotted in Figure 1, Curve 1. This graph is a part of Figure 5, Concrete Pipe, Friction factors, of Monograph No. 7.

The coefficients decrease consistently with the generally accepted trend of the Moody diagram based on the Prandtl-Von Karman experiments, Colebrook and White function, and experiments on commercial pipes. The values of the resistance coefficients are slightly higher than might be expected from a tunnel of this diameter. A review of test conditions, taking account of possible errors in the method of measurement, failed to show reason why the resistance coefficient could not be accepted within 5 to 8 percent of a true value.

New York Water Board Tunnels.

The Bureau of Reclamation received from the Board of Water Supply, City of New York, the results of headloss measurement on the Neversink and East Delaware tunnels, a part of the New York municipal supply system. As part of continuing effort of the Bureau to improve the evaluation of resistance losses in conveyances, these data were analyzed.

Details of the analysis will not be repeated in this report, except where they differ from standard procedure. Results of the analysis for Neversink Tunnel are contained in Tables 2, 3, 4, and 5, and for the East Delaware Tunnel in Table 6. Figure 1, Curves 2, 3, 4, 5 and 6 compare the tunnel resistance coefficients.

Neversink Tunnel

Tests were made on the Neversink Tunnel on December 17 and 18, 1956, after the tunnel had been in service about 9 years and on July 24 and 25, 1957. Chlorination of the tunnel was started on February 1, 1957, and although not so stated, it was implied to have continued periodically to the time of the July tests. The tunnel was operated usually 5 days per week, occasionally 6 days for about 13 hours per day.

The tunnel contained 24,584.54 feet of 10.0 foot diameter and 1347.33 feet of 8.0 foot diameter concrete lining. Three changes of grade from 2.1 percent to level to 1.5 percent occurred in the length of the 10-foot-diameter tube. The section of 8-foot-diameter pipe was level. One change of alinement of the 10-foot-diameter tunnel was accomplished with a 100-foot radius curve and deflection angle of 111.5 degrees formed with 10-foot chords and wood filler pieces between straight steel forms. No attempt was made to modify the measured head loss by a computed elbow loss.

To obtain the loss in the reach of 10-foot-diameter tunnel, water surface levels at the upstream end were measured in an open stilling well with an electrical tape. At the lower end, a conical transition 10 feet long reduced the tunnel from 10 to 8 feet in diameter. To evaluate the losses in the 8-foot-diameter reach, piezometers were placed 600 feet apart on the horizontal centerline near the downstream end away from the transition. A differential gauge was used in determining the loss in the 600-foot reach with a Bourdon gauge at the downstream piezometer to measure the pressure head. The head loss in the 600-foot reach of 8-foot pipe was prorated to the total length of 1,347 feet. The 10- to 8-foot transition in the direction of flow was considered an extra 10-foot length of 8-foot pipe and not evaluated as a transition. The transition was considered mild and not liable to an accurate evaluation of the head loss other than additional friction. Coefficients of resistance were evaluated from the head loss between the pressures measured at the entrance stilling well and computed at the upstream end of the 10-foot to 8-foot transition.

In the 1956 tests, the flow was measured by both the salt and color velocity methods, the salt and dye being injected together. Readings of Venturi meter instruments, indicator totalizer and manometer were made, but the results of the salt and color velocity measurements were considered more accurate and were furnished with the test data. In the 1957 tests, only the color velocity method was used and measurements made for nominal flows of 300, 400, and 500 million gallons per day. Intermediate discharges were interpolated.

An inspection of the tunnel showed blackish, somewhat slippery or slimy coating about 1/16-inch thick. On drying, it crazed and shrunk in thickness and could be readily removed. Moisture-free samples after an ignition loss of about 17 percent, contained about 41 percent silica and silicate, 36 percent manganese, 8 percent aluminum and 7 percent calcium.

Coefficients of friction evaluated for the Neversink Tunnel for use with the Darcy-Weisbach equation are contained in Tables 2, 3, 4, and 5 for the 8 and 10-foot-diameter test reaches. The tables also contain values of Manning's "n".

East Delaware Tunnel

Tests were made on the East Delaware Tunnel on December 2 and 5, 1955. The tunnel was in service on January 8, 1955, but was emptied several times in the interim before testing. Discharges were measured by the salt velocity method. Head loss was measured between the water surface level in an open stilling well at the upstream end of the pipe and a pressure gauge reading near the downstream end.

A reach of 131, 265.21 feet of the 11.33-foot-diameter tunnel was selected for this test. Several changes of grade occur in this tunnel. Beginning at the upstream end, changes in slope of 0.15, -0.50, level, -0.50, level and -0.30 percent, drop the tunnel invert from elevation 1143.0 at the entrance to approximately 840 at the exit. This tunnel was essentially straight in alinement except for one elbow of 50-foot radius and a deflection angle of approximately 43.5 degrees. Three other deflections of the alinement occur downstream of the elbow. These deflections were small and accomplished by wooden filler pieces separating the steel forms. No transitions or changes of area occurred in the test reach.

Coefficients of resistance computed from data supplied for this tunnel are contained in Table 6.

Linings of the Tunnels

Both of the New York Water Board tunnels were lined with concrete, the sidewalls and arch were placed against steel forms in one operation. The invert was screeded. In the East Delaware Tunnel, the invert was placed first and then the side walls and arch. In the Neversink Tunnel, the procedure was reversed. In the East Delaware, the side walls and arch were concreted by the continuous-pour method, while in the Neversink, the concreting was in reaches of 200 feet.

Comparison of Results, Engineering Monograph 7

Resistance coefficients for the two tests and three diameters of conduit have been plotted on Figure 1. Correlation of the computed data is in general agreement with that used previously in the monograph.

Data for the 8-foot diameter tunnel is slightly high relative to other pipes of the same diameter falling in a lower Reynolds number range. This apparent increase may be reasonable. It is known that in the vicinity of entrances to pipes and changes in section, the boundary layer is in part or wholly destroyed. In reestablishment of the boundary layer, values of the resistance coefficient in the zone of establishment may rise to approximately 2 times that found where the boundary layer is fully established. A modification of the established flow in the 10-foot-diameter tunnel may have occurred at the 10- to 8-foot transition. Resistance values thus measured would be slightly higher than that for a longer reach of tunnel because of the proportionate higher resistance of approximately 1/3 of the test length downstream of the transition.

Some aging effect may be evident in both the 8- and 10-foot-diameter tunnels, assuming equal accuracy of measurement in 1956 and 1957. For both tunnel sizes, the 1957 data show a higher resistance coefficient than the 1956 data. The 10-foot tunnel shows an increase that might reasonably be expected. Differences in the resistance coefficients for the 8-foot-diameter tunnel from 1956 to 1957 seem higher than normally would be expected.

Resistance coefficients for the 11.33-foot-diameter tunnel fall well within the range that would be expected for this size tunnel. All data from these tests seem well defined and acceptable for inclusion in our evaluation of resistance coefficients.

SIPHONS AND PIPELINES

Weber Coulee Siphon

Weber Coulee Siphon is a part of the East Low Canal in the Columbia Basin Project of the Bureau of Reclamation. This canal conveys water for irrigation from Long Lake which is filled from the Equalizing Reservoir supplied by Lake Roosevelt behind Grand Coulee Dam.

From a total siphon length of 5,956 feet, 5,641 feet was used as a test reach. Changes of slope in the siphon ranged from a -0.07431 to a +0.18504 for a 50 foot length which was included in a mild reverse bend 152 feet long near the low point of the siphon. The siphon is straight in alinement and all vertical deflection angles between slopes were accomplished in 5^{o} or less. The difference in invert elevations from the inlet to exit is 12.56 feet.

Diameters measured in the test reach averaged 14.67 feet, the design diameter. Variations in the diameters used in the average were a maximum of 3.1 percent. Sections of the siphon barrel were cast against steel forms in 25 foot lengths. Rubber water stops were cast in the concrete near the center of the lining thickness which ranged from 15 to 19 inches. Inspection of the lining at the time of the test disclosed a smooth surface consistent with steel form construction. Alinement of the joints was good, and only slight irregularities were caused by deflection of the forms in matching from one section to the next. Small voids were in evidence in a few areas of the lining where the concrete failed to completely contact the form. These areas were a small percentage of the total surface area. The concrete surface was clean and free of biological growths.

Pressures were measured at six sections of the test reach by both water and mercury manometers. The first section of measurement was 218 feet downstream of the siphon entrance. Water manometers were used at the beginning and end of the test reach selected for friction evaluation. Four piezometers were installed at each section in the concrete lining during construction. Leads from the piezometers were connected to the manometers by a valved manifold to permit a check of individual pressure heads throughout the tests. All manometers were referenced to one elevation by use of an engineer's level.

Discharges for the tests were measured by the salt-velocity method. Salt injection and electrode apparatus was installed near the entrance of the siphon. Submergence of the inlet and transition was accomplished by restricting the siphon exit with stoplogs in slots provided during construction. Five salt injections were made for each stabilized discharge through the siphon. Arithmetical averages of the indications of the five injections were used to establish the discharge for each test.

Resistance coefficients computed from the data resulting from these tests show good conformity, Table 7. Darcy-Weisbach "f" values ranged from 0.0106 to 0.0108 comparable with the normally accepted values for this diameter conduit. The Reynolds numbers of these tests were limited but they are in a range where there is a deficiency of information Figure 1, Curve 7.

San Diego Aqueduct

The San Diego Aqueduct conveys water from the Colorado River Aqueduct near the downstream portal of the San Jacinto Tunnel to the San Vicente Reservoir. The aqueduct consists of long inverted siphons of precast concrete pipe of 48-, 54-, 60-, and 72-inch diameters, steel pipe of 48-inch diameter, and tunnels of horseshoe shape having a finished diameter of 6 feet. The total length of the aqueduct is 71.1 miles and the available head is approximately 750 feet. The carrying capacity of the two lines of the aqueduct at the time of the tests was about 200 cfs, or some 100 cfs per line.

Three series of hydraulic tests were made on the aqueduct. Two tests were made in 1947 and 1949, after completion of the first of two pipelines forming the aqueduct, and the results were included in Engineering Monograph No. 7. A third test was made in 1955 after completion of the full capacity system.

Tests were made in December 1947, of overall losses in the first pipeline. In 1948, some loss of capacity was encountered due to the growth of algae. This capacity loss was restored by chlorination. A check was made on the friction coefficient again in March and April 1949. In 1955, the full capacity aqueduct was tested for head loss to determine friction coefficients. At this time tests were conducted both on the new pipeline, and selected reaches of the old pipeline. Testing in 1955 was done by representatives of the U. S. Bureau of Reclamation, the San Diego County Water Authority, and the Metropolitan Water District of Southern California.

Discharges were measured by the salt velocity method and checked by the 36- by 72-inch venturi meters at the regulating reservoir. No provision was made for measuring head loss in the conduits at the time of construction. However, there were numerous open vents, air inlet and release valves, blowoffs and other structures affording access to the water prism. An electrical contact gage was used to measure water surface elevations in vent structures. Mercury manometers were used at the other structures to measure the pressure head to establish the hydraulic gradient. Head losses obtained from these measurements and the average velocities from the discharge measurements was used to evaluate the resistance coefficient.

Seven different siphons of precast concrete pipe of 4 different diameters were used in the tests. Four siphons were new pipe and three of the siphons were old pipe. The hydraulic characteristics of these sections were very similar.

A general description of these siphons follows:

NEW PIPE

North Station 779+99.23 to Station 860+37.50 Total laid length is 8000.3 feet. Nominal diameter 60-inches.
North Station 980+76.16 to Station 1043+66.41. Total laid length is 6293.4 feet. Nominal diameter 60-inches.
North Station 1163+54.97 to Station 1208+19.82. Total laid length is 4476.4 feet. Nominal diameter 48-inches.
North Station 1227+92.74 to Station 1534+33.21. Total laid length is 30,754.1 feet. Nominal diameter 60-inches.

OLD PIPE

North Station 528+22.60 to Station 602+13.00. Total laid length is 7376.5 feet. Nominal diameter 72-inches.
North Station 961+00 to Station 1146+50. Total laid length is 18,510.45 feet. Nominal diameter 54-inches.
North Station 1545+15 to Station 1702+77. Total laid length is 15,767.81 feet. Nominal diameter is 54-inches.

Details of the analysis are not repeated, but the results are contained in Tables 8, 9, 10, 11, and 12, and in Figure 1, Curves 8, 9, 10, 11, 12, and 13. Both discharge and head loss measurements made for the tests were of high quality resulting in excellent friction loss data.

SUMMARY

Results of the evaluation of resistance coefficients in this report are in agreement with measurements from other large conduits. The resistance coefficients confirm and strengthen the findings of Engineering Monograph No. 7, and show no need to alter the earlier plots. Reports supplemental to Monograph No. 7 will be released as information is acquired from Bureau of Reclamation test installations and other sources.

Table 1

EKLUTNA TUNNEL, ALASKA--1957

Test reach of 2,534 diameters of 9-foot 0-inch-diameter conduit

Velocity ft/sec	Head loss, ft	Reynolds Number* $\times 10^6$	Darcy-Weisbach f	Manning's n
1.261	1.07	0.709	0.0171	0.0139
2.615	4.11	1.47	0.0153	0.0131
3.708	8.39	2.09	0.0155	0.0132
4.936	15.30	2.74	0.0159	0.0134
6.138	25.56	3.45	0.0159	0.0134
7.233	31.21	4.06	0.0151	0.0131
8.246	36.69	4.64	0.0137	0.0124

*Water temperature 42.8° F

Table 2

1956

NEVERSINK TUNNEL--BOARD OF WATER SUPPLY--NEW YORK

Test reach of 170 diameters of
8-foot- 0-inch-diameter conduit

Velocity ft/sec	Head loss, ft	Reynolds Number $\times 10^6$	Darcy-Weisbach f	Manning's n
6.450	1.656	3.13*	0.0151	0.0127
6.578	1.693	3.19	0.0149	0.0127
7.616	2.251	3.69	0.0147	0.0126
7.859	2.311	3.81	0.0142	0.0124
9.077	3.078	4.40	0.0142	0.0124
9.170	3.226	4.45	0.0146	0.0125
12.322	5.207	5.97	0.0130	0.0118
12.412	5.538	6.02	0.0136	0.0121
15.373	8.736	7.45	0.0140	0.0123

*Water temperature 41° F.

Table 3

1957

6.129	1.55	4.46**	0.0157	0.0130
8.992	3.15	6.54	0.0148	0.0126
8.992	3.27	6.54	0.0154	0.0129
10.546	4.22	7.81	0.0144	0.0125
12.098	5.47	8.96	0.0142	0.0124
12.098	5.44	8.96	0.0141	0.0123
13.646	6.57	9.92	0.0134	0.0120
15.198	8.60	11.05	0.0141	0.0124
15.198	8.54	11.05	0.0140	0.0123

**Water temperature 67° F.

Table 4

1956

NEVERSINK TUNNEL--BOARD OF WATER SUPPLY--NEW YORK

Test reach of 2,458 diameters of 10-foot- 0-inch-diameter conduit

Velocity ft/sec	Head loss, ft	Reynolds Number $x10^6$	Darcy-Weishbach f	Manning's n
4.133	8.51	2.51*	0.0131	0.0123
4.210	9.43	2.55	0.0139	0.0127
4.874	11.45	2.95	0.0126	0.0121
5.030	12.19	3.05	0.0126	0.0121
5.810	15.56	3.52	0.0121	0.0118
5.869	15.66	3.56	0.0119	0.0118
7.886	26.48	4.78	0.0112	0.0114
7.944	28.10	4.82	0.0117	0.0116
9.839	38.80	5.96	0.0105	0.0110

*Water temperature 41° F.

Table 5

1957

3.923	7.30	3.57**	0.0124	0.0120
5.755	14.55	5.23	0.0115	0.0116
5.755	14.33	5.23	0.0113	0.0115
6.750	19.62	6.25	0.0113	0.0114
7.743	25.14	7.17	0.0110	0.0113
7.743	25.25	7.17	0.0110	0.0113
8.734	31.50	7.94	0.0108	0.0112
9.727	37.36	8.84	0.0104	0.0110
9.727	36.73	8.84	0.0102	0.0109

**Water temperature 67° F.

Table 6

EAST DELAWARE TUNNEL--BOARD OF WATER SUPPLY--NEW YORK
Test reach 11,585 diameters of 11-foot-4-inch-diameter conduit--1955

Velocity ft/sec	Head loss, ft	Reynold's Number* $x10^6$	Darcy-Weisbach f	Manning's n
2.516	14.01	2.01	0.0123	0.0122
2.516	14.01	2.01	0.0123	0.0122
4.351	41.41	3.52	0.0122	0.0121
4.351	41.41	3.52	0.0122	0.0121
6.375	82.59	5.09	0.0113	0.0117
6.374	82.59	5.09	0.0113	0.0117
7.661	119.15	6.11	0.0113	0.0117
7.660	119.15	6.11	0.0113	0.0117
10.568	222.02	8.43	0.0111	0.0116
10.562	222.02	8.43	0.0111	0.0116

*Water temperature 50° F.

Table 7

WEBER COULEE SIPHON
Test reach, 385 diameters of 14.67-foot-diameter conduit October 1956

3.943	1.00	4.66	0.0108	0.0119
5.499	1.95	6.64	0.0108	0.0119
6.47	2.68	7.65	0.0107	0.0119
7.37	3.45	8.72	0.0106	0.0118

*Water temperature 58° F.

Table 8

SAN DIEGO AQUEDUCT--1955

Inverted Siphon Between North Station 1163+54.97 and North Station 1208+19.82 New Barrel--Concrete Pipe

Laid Length of Reach--4,476.4 feet--1,119D

Nominal Diameter of Pipe--48 inches

Velocity ft/sec	Total head loss, ft	Reynold's Number * x10^6	Friction factor $f = h_f / \frac{LV^2}{D2g}$	Manning's n
6.16	9.15	1.832	0.014	0.0109
7.30	12.94	2.17	.014	.0110
6.42	9.69	1.907	.014	.0108
5.59	7.35	1.662	.014	.0108
4.87	5.27	1.447	.013	.0105
8.16	15.95	2.425	.014	.0109
3.93	3.82	1.168	.014	.0110
3.14	2.36	0.934	.014	.0109
2.34	1.33	0.697	.014	.0109
7.48	13.69	2.222	.014	.0110
7.97	15.55	2.369	.014	.0110
8.24	16.67	2.448	.014	.0110

*Water temperature 53° F.

Table 9

SAN DIEGO AQUEDUCT--1955
New barrel--Concrete Pipe
Inverted Siphon Between North Station 980+76.16 and North Station 1043+66.41
Laid Length of Reach--6,293.4 feet--1,259D
Nominal Diameter of Pipe--60 inches

Velocity ft/sec	Total head loss, ft	Reynold's Number* x10^6	Friction factor $f = h_f / \frac{LV^2}{D2g}$	Manning's n
3.95	4.76	1.467	0.016	0.0120
4.68	6.69	1.737	.016	.0120
4.11	5.02	1.527	.015	.0118
3.58	4.02	1.331	.016	.0122
3.12	3.16	1.159	.016	.0124
5.23	7.70	1.942	.014	.0115
2.52	1.91	0.936	.015	.0119
2.01	1.28	0.748	.016	.0122
1.50	0.80	0.558	.018	.0129
4.79	7.10	1.780	.016	.0121
5.11	8.06	1.897	.016	.0121
5.28	8.71	1.961	.016	.0122

*Water temperature 53° F.

Table 10

SAN DIEGO AQUEDUCT--1955
New barrel--Concrete Pipe
Inverted Siphon Between North Station 779+99.23 and North Station 860+37.50
Total Laid Length of Reach--8,023.3 feet--1,605D
8,000.3 feet of 60-inch Pipe
17.5 feet of 48-inch Pipe
5.5 feet of 60-inch by 48-inch Transition

Velocity ft/sec	Total head loss, ft	Reynold's Number* $\times 10^6$	Friction factor $f = h_f / \frac{LV^2}{D2g}$	Manning's n
3.95	6.30	1.467	0.0160	0.0121
4.68	8.65	1.737	.0158	.0120
4.11	6.36	1.527	.0149	.0117
3.58	4.84	1.331	.0149	.0117
3.12	3.71	1.159	.0151	.0118
2.52	2.42	0.936	.0151	.0118
2.01	1.56	0.748	.0152	.0118
1.51	0.88	0.558	.0155	.0120
4.79	8.60	1.780	.0148	.0117
5.11	9.35	1.897	.0142	.0114
5.28	10.67	1.961	.0155	.0118

*Water temperature 53° F.

Table 11

SAN DIEGO AQUEDUCT--1955
New Barrel--Concrete Pipe
Inverted Siphon Between North Station 1227+92.74 and North Station 1534+33.21
Laid Length of Reach--30,754.1 feet--6,151D
Nominal Diameter of Pipe--60 inches

Velocity ft/sec	Total head loss, ft	Reynold's Number* $\times 10^6$	Friction factor $f = h_f / \frac{LV^2}{D2g}$	Manning's n
3.95	20.89	1.467	0.0140	0.0115
4.68	28.67	1.737	.0139	.0113
4.11	22.18	1.527	.0137	.0113
3.58	17.32	1.331	.0141	.0114
3.12	12.78	1.159	.0137	.0113
5.23	35.69	1.942	.0137	.0112
2.52	8.56	0.936	.0141	.0114
2.01	5.62	0.749	.0145	.0116
1.50	3.30	0.558	.0153	.0120
4.79	30.82	1.780	.0140	.0114
5.11	34.76	1.897	.0139	.0114
5.28	37.33	1.961	.0143	.0114

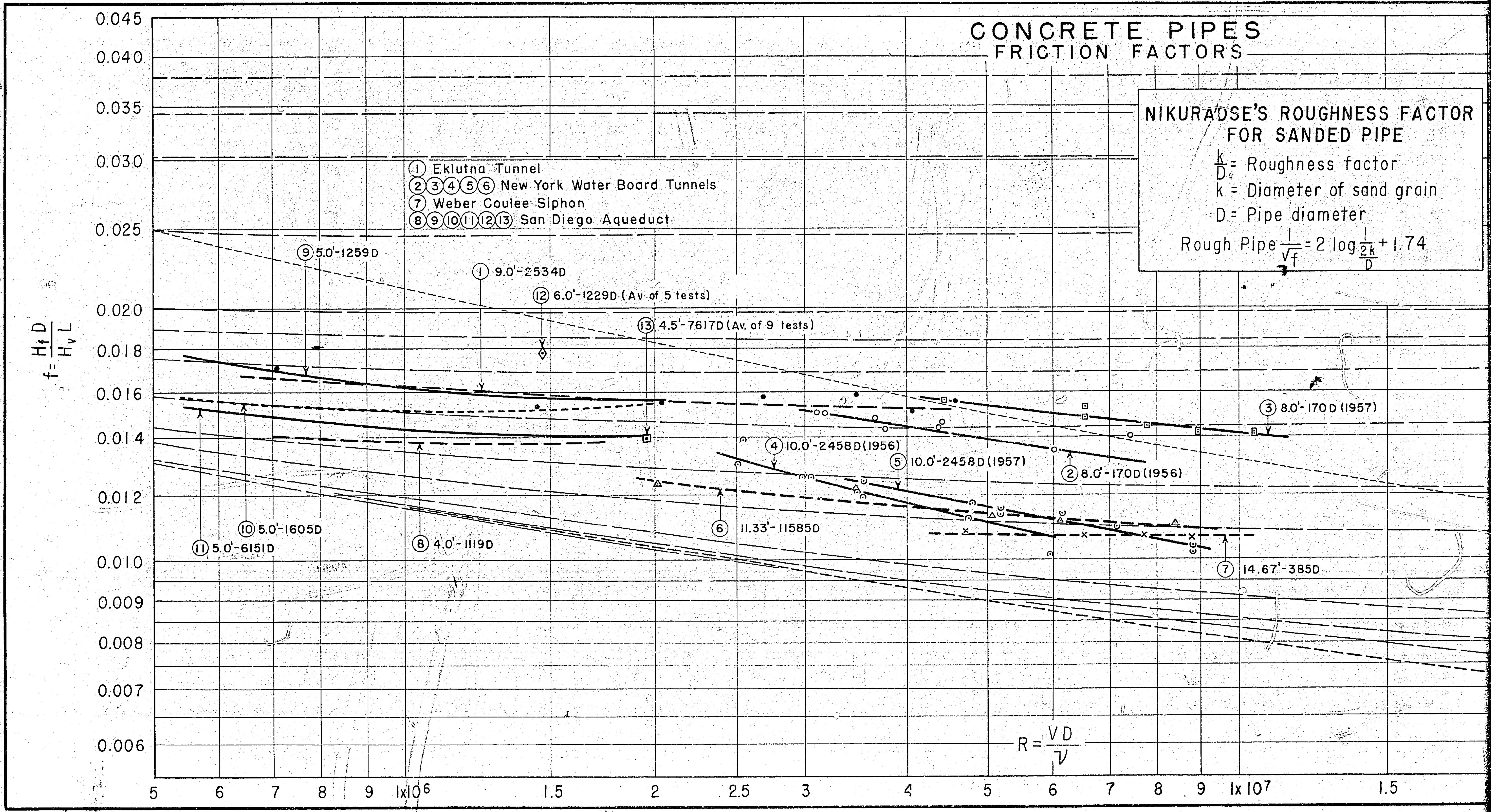
*Water temperature 53° F.

Table 12

SAN DIEGO AQUEDUCT--1955
Old Barrel--Concrete Pipe

Velocity ft/sec	Total head loss, ft	Reynold's Number* $\times 10^6$	Friction factor $f = h_f / \frac{LV^2}{D2g}$	Manning's n
Siphon Between North Station 528+22.60 and 602+13.00--Laid Length 7,376.5 feet, 1,229D-Nominal Diameter 72 in				
3.35	3.68	1.494	0.0172	0.0130
3.14	3.28	1.400	.0174	.0131
3.19	3.47	1.432	.0176	.0131
3.31	3.69	1.475	.0177	.0131
3.30	3.70	1.472	.0178	.0132
North Station 961+00 to 1146+50=Laid Length 18,510.45 feet, 4113D--Nominal Diameter 54 in				
5.84	30.88	1.952	0.0142	0.0112
5.57	27.57	1.862	.0139	.0111
5.70	28.86	1.905	.0139	.0111
5.87	30.18	1.962	.0137	.0111
5.86	30.28	1.959	.0138	.0111
North Station 1545+15 to 1702+77--Laid Length 15,767.81 ft, 3504D-Nominal Diameter 54 in				
5.84	26.01	1.952	0.0140	0.0112
5.70	24.06	1.905	.0136	.0110
5.87	25.71	1.962	.0137	.0111
5.86	25.66	1.959	.0137	.0111

*Water temperature 53° F.


CONCRETE PIPES
FRICTION FACTORS
NIKURADSE'S ROUGHNESS FACTOR FOR SANDED PIPE
$\frac{k}{D}$ = Roughness factor
k = Diameter of sand grain
D = Pipe diameter
Rough Pipe $\frac{1}{\sqrt{f}} = 2 \log \frac{1}{\frac{2k}{D}} + 1.74$
① Eklutna Tunnel
②③④⑤⑥ New York Water Board Tunnels
⑦ Weber Coulee Siphon
⑧⑨⑩⑪⑫⑬ San Diego Aqueduct
$f = \frac{H_f D}{H_v L}$
$R = \frac{VD}{\nu}$
⑨ 5.0'-1259D
① 9.0'-2534D
⑫ 6.0'-1229D (Av. of 5 tests)
⑬ 4.5'-7617D (Av. of 9 tests)
③ 8.0'-170D (1957)
④ 10.0'-2458D (1956)
⑤ 10.0'-2458D (1957)
② 8.0'-170D (1956)
⑩ 5.0'-1605D
⑪ 5.0'-6151D
⑧ 4.0'-1119D
⑥ 11.33'-11585D
⑦ 14.67'-385D
0.045
0.040
0.035
0.030
0.025
0.020
0.018
0.016
0.014
0.012
0.010
0.009
0.008
0.007
0.006
5
6
7
8
9
1x10^6
1.5
2
2.5
3
4
5
6
7
8
9
1x10^7
1.5

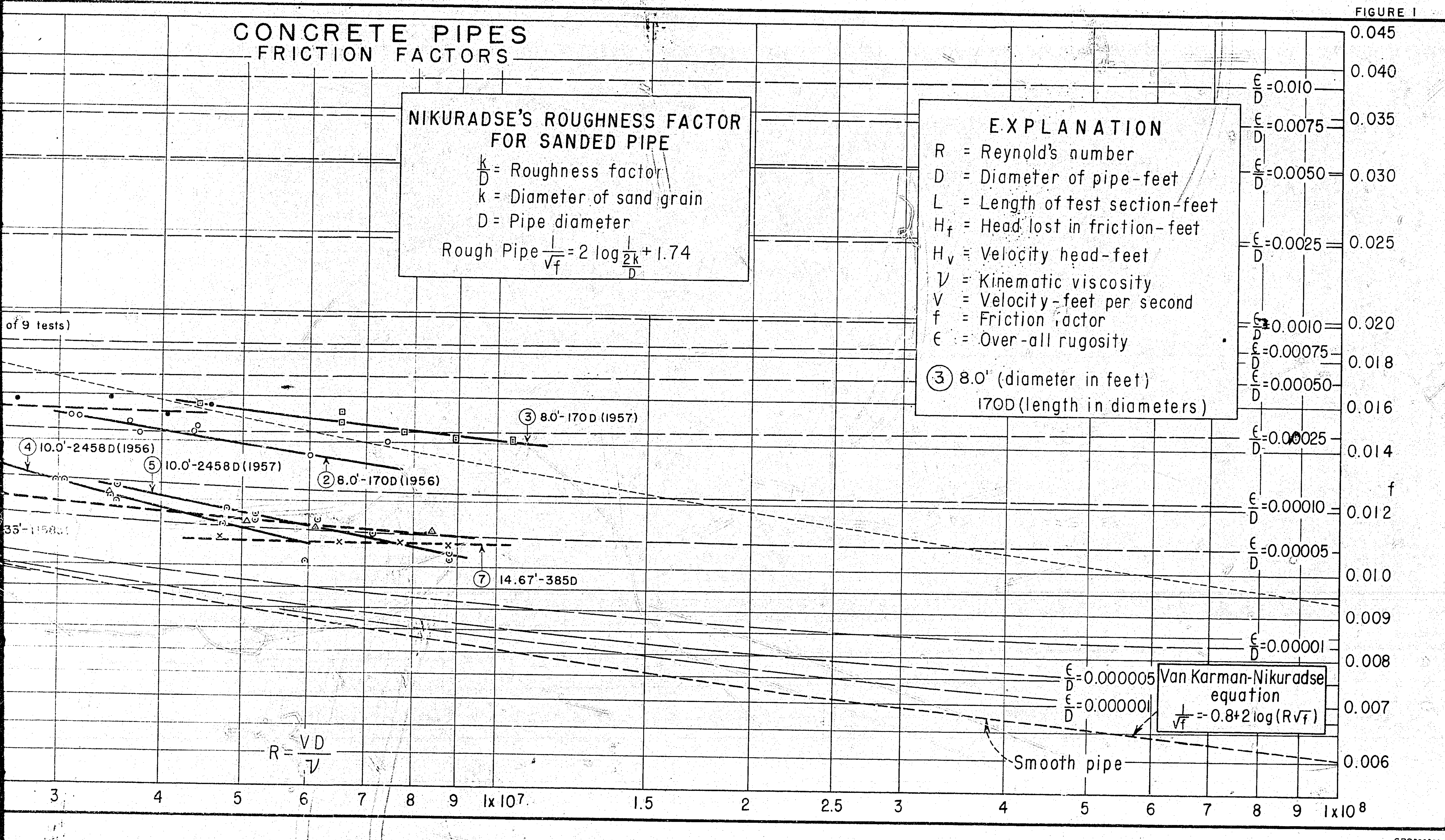


FIGURE I
CONCRETE PIPES
FRICTION FACTORS
NIKURADSE'S ROUGHNESS FACTOR FOR SANDED PIPE
$\frac{k}{D}$ = Roughness factor
k = Diameter of sand grain
D = Pipe diameter
Rough Pipe $\frac{1}{\sqrt{f}} = 2 \log \frac{1}{\frac{2k}{D}} + 1.74$
EXPLANATION
R = Reynold's number
D = Diameter of pipe-feet
L = Length of test section-feet
H_f = Head lost in friction-feet
H_v = Velocity head-feet
ν = Kinematic viscosity
V = Velocity-feet per second
f = Friction factor
ϵ = Over-all rugosity
(3) 8.0' (diameter in feet)
170D (length in diameters)
of 9 tests)
(3) 8.0'-170D (1957)
(4) 10.0'-2458D (1956)
(5) 10.0'-2458D (1957)
(2) 8.0'-170D (1956)
(7) 14.67'-385D
35'-1158D
$\frac{\epsilon}{D}$=0.010
$\frac{\epsilon}{D}$=0.0075
$\frac{\epsilon}{D}$=0.0050
$\frac{\epsilon}{D}$=0.0025
$\frac{\epsilon}{D}$=0.0010
$\frac{\epsilon}{D}$=0.00075
$\frac{\epsilon}{D}$=0.00050
$\frac{\epsilon}{D}$=0.00025
$\frac{\epsilon}{D}$=0.00010
$\frac{\epsilon}{D}$=0.00005
$\frac{\epsilon}{D}$=0.00001
$\frac{\epsilon}{D}$=0.000005
$\frac{\epsilon}{D}$=0.000001
Van Karman-Nikuradse equation
$\frac{1}{\sqrt{f}} = -0.8 + 2 \log (R\sqrt{f})$
Smooth pipe
$R = \frac{VD}{\nu}$
f
0.045
0.040
0.035
0.030
0.025
0.020
0.018
0.016
0.014
0.012
0.010
0.009
0.008
0.007
0.006
3
4
5
6
7
8
9
1x10^7
1.5
2
2.5
3
4
5
6
7
8
9
1x10^8
GPO836968

FRAME 2